REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-

8090

1. REPORT DATE *(DD-MM-YYYY)* 31/12/2000	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)* 10/1/1997 - 9/30/2000
4. TITLE AND SUBTITLE Mechanisms of Perceptual Attention		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER F49620-98-1-0016
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Barbara Anne Dosher		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Dept. of Cognitive Science, Univ. of California Irvine, Irvine, CA 92697-5100		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NL, 110 Duncan Avenue, Room B115, Bolling AFB, DC 20332-8050		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Attending to some visual inputs rather than others has significant consequences for performance in everyday and industrial tasks that require the monitoring of complex displays. Attention may affect the perceived clarity of visual displays and improve performance. In this project, a powerful external noise method was developed to identify and characterize the effect of attention on perceptual performance in visual tasks. The effect on task performance of adding external noise-- random visual noise (similar to random TV noise) -- associates each mechanism of attention with a "signature" pattern of performance as external noise exclusion, stimulus enhancement, or internal noise reduction. We evaluated the mechanisms of attention in a variety of perceptual tasks (simple orientation identification, motion direction discrimination, and letter recognition) when attention is focused on a location in the visual array. Evidence was found for external noise exclusion as a primary mechanism of attention in noisy or masked stimulus situations, with stimulus enhancement as a secondary mechanism of attention associated with peripheral cueing. The methods were elaborated to measure the spatial frequency sensitivity of the observer's matching templates and modification of the templates by attention. The theory and methods developed in this project provide a task taxonomy that may provide an analysis of behavior in applied settings.

15. SUBJECT TERMS

Perceptual Attention

16. SECURITY CLASSIFICATION OF: U			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Barbara Anne Dosher
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	~~18~~ 17	**19b. TELEPHONE NUMBER** *(include area code)* (949) 824-7373
Unclas	Unclas	Unclas			

USAF Office of Scientific Research
Life Sciences Directorate, Visual Information Processing Program
Final Technical Report, 1 Oct 1997 – 30 Sept 2000
Grant AFOSR **F49620-98-1-0016**

Mechanisms of Perceptual Attention

PI: Barbara Anne Dosher, University of California, Irvine, CA♦

1. ABSTRACT

Attending to some visual inputs rather than others has significant consequences for performance in everyday and industrial tasks that require the monitoring of complex displays. Attention may affect the perceived clarity of visual displays and improve performance. In this project, a powerful external noise method was developed to identify and characterize the effect of attention on perceptual performance in visual tasks. The effect on task performance of adding external noise-- random visual noise (similar to random TV noise) -- associates each mechanism of attention with a "signature" pattern of performance as external noise exclusion, stimulus enhancement, or internal noise reduction. We evaluated the mechanisms of attention in a variety of perceptual tasks (simple orientation identification, motion direction discrimination, and letter recognition) when attention is focused on a location in the visual array. Evidence was found for external noise exclusion as a primary mechanism of attention in noisy or masked stimulus situations, with stimulus enhancement as a secondary mechanism of attention associated with peripheral cueing. The methods were elaborated to measure the spatial frequency sensitivity of the observer's matching templates and modification of the templates by attention. The theory and methods developed in this project provide a task taxonomy that may provide an analysis of behavior in applied settings.

2. OBJECTIVES

Objectives were consistent with the original proposal to study the mechanisms of visual attention.

3. OVERVIEW

- The research introduced and applied a powerful method for identifying and characterizing the effect of attention on performance in visual tasks as due to stimulus enhancement, external noise exclusion, or internal noise suppression. The method adds systematically increasing amounts of (random or filtered random) external noise to the visual stimulus and observes the effect on a perceptual task under different attention manipulations. The effects on task performance of adding external noise under different attention conditions were modeled quantitatively, yielding an estimate of the attention effect and a quantification of some perceptual task limits.

♦ NOTE: This was a collaborative research project between Barbara Anne Dosher at the University of California, Irvine and Zhong-Lin Lu at the University of Southern California, independently funded at the separate institutions.

- This method of characterizing the mechanisms of attention was applied to a variety of perceptual tasks, including detecting or identifying objects of differing (a) orientation, (b) shape,, (c) motion, or (d) character identification, and a variety of task situations involving manipulation of attention: (1) pre-cue stimulus onset asynchrony (2) cue validity and misleading cues, (3) central and peripheral cueing, or (4) display load.

- The method was extended through the use of filtered external stimulus noise to evaluate possible changes in spatial frequency tuning under different attention conditions, and was extended to applications in perceptual learning.

- Collateral model tests were performed that tested quantitative properties of a perceptual template model, including the relationship of certain ratio properties in performance to system nonlinearities, and extensions to fully stochastic formulations.

4. ACCOMPLISHMENTS

4.1. Attention in Perceptual Tasks

Attention to objects or features of objects affects performance on perceptual tasks such as detection, recognition, or identification. The speed or accuracy of task performance can be significantly influenced by changes in the state of attention, especially in complex task environments. The state of attention may be manipulated by specific environmental cues, or by decisions about allocation of attention induced by task demands. The challenge is to understand and predict these attention-mediated changes in task performance, and to identify the mechanisms by which attention is operating. The goal of the project was to provide a functional model and empirical basis for the classification of mechanisms of perceptual attention in a variety of representative perceptual tasks, including discrimination and identification of both simple and complex visual patterns. The operation of these attention mechanisms were measured in a representative range of perceptual tasks, including basic perceptual tasks such as detection or discrimination of stimuli varying along basic visual dimensions (orientation, spatial frequency), and the identification of more complex stimuli such as letters or visual forms. The analysis of mechanisms of attention can constrain process models of attention and may additionally suggest constraints on the relevant properties of neurological models of attention.

4.2. Mechanisms of Attention.

The study of attention dates back more than 100 years. The earliest physiologists and psychologists recognized the importance of attention in perception.. Those investigators were divided as to whether attention affected the perceived quality of objects, such as perceived color or brightness, or whether it simply made information more accessible. The study of selective attention to a location in space, or to an object, has been the subject of extensive study since the 1970s. Performance improvements due to attention to a location have been attributed in previous research to several different attention processes. (1) <u>statistical uncertainty</u> , in which attention reduces the number of irrelevant sources of false alarms contributing to the decision mechanisms; (2) <u>facilitation of sensory analysis</u> (stimulus enhancement) in which attention results in a stronger sensory representation; (3) <u>limited capacity processes</u> that improve

performance by redistributing mental resources; (4) elimination of noise from distracting locations or from masks. Each of these mechanisms has been used as an explanation of attention effects in at least some task circumstances.

In this project, experimental designs were devised that eliminated statistical uncertainty, and provided definitive tests to distinguish stimulus enhancement and noise elimination as the underlying mechanism of visual attention. An external noise analysis and theoretical framework were developed and applied to a range of visual performance tasks (Dosher & Lu, 1999, 2000a, 2000b; Lu & Dosher, 1998, 1999, 2000). A systematic analysis of attention was developed in terms of three mechanisms: stimulus enhancement, external noise exclusion, and (multiplicative) internal noise reduction. One advantage of the theoretical framework we adopt is that it formally quantifies, and provides specific tests for, each possible mechanism of attention.

4.3. Overview of Accomplishments

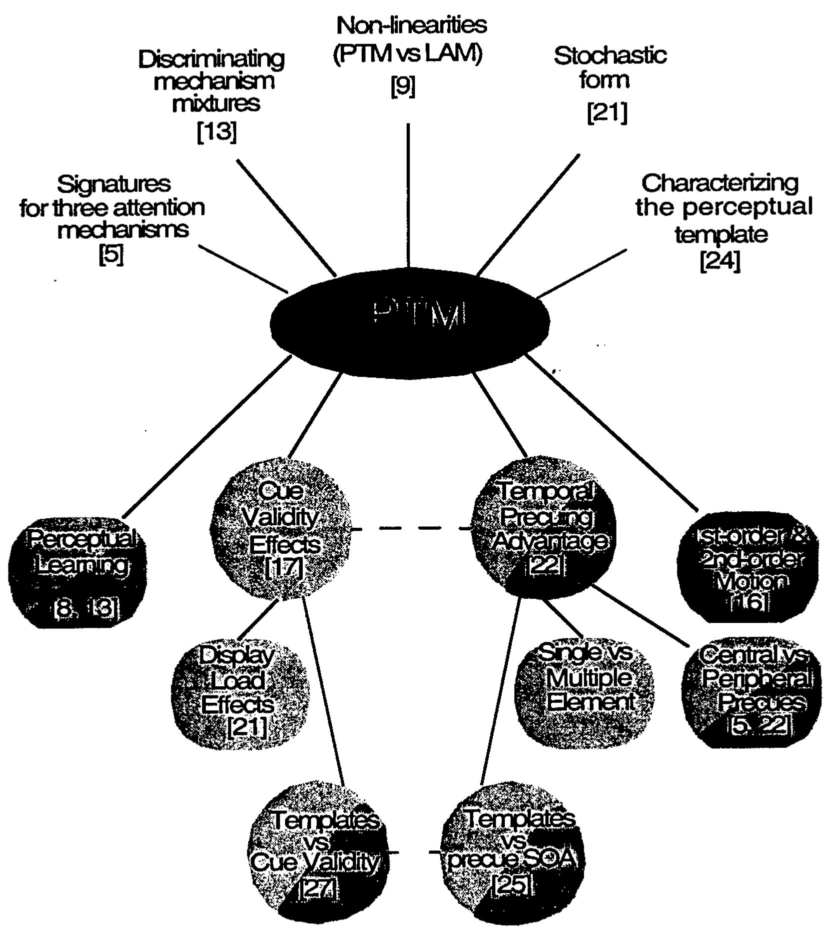

Figure 1. A roadmap of work from the prior grant period. Theoretical findings (top) and empirical findings of external noise exclusion (light gray) and stimulus enhancement (dark gray) (bottom).

In this project, we developed external noise methods and a perceptual template model (PTM) of the observer in order to study the perceptual mechanisms underlying modifications of performance by attention, task demand, or learning. Our initial applications of the external noise methods were to classic effects associated with attention to spatial location. References to the publications from the previous joint project on mechanisms of visual attention appear as lists of publications and transactions in the sections below, and are referenced here by number (e.g., [5]). A map illustrating connections between key findings and development is shown in Figure 1, above. The top elements refer to theoretical and modeling developments, the bottom elements refer to empirical developments.

The initial work in this project developed the method and framework, and provided a demonstration of attention effects in several classical paradigms of visual attention. Signature performance patterns were derived for three mechanisms of attention (external noise exclusion, stimulus enhancement, and multiplicative internal noise reduction) [1, 2, 5]. Fig. 2 (below) illustrates the empirical consequences of the three mechanisms.

Pure cases of external noise exclusion [6, 11, 17, 21] (Fig. 2d-f) and pure cases of stimulus enhancement [1, 2, 5, 10] (Fig. 2a-c) were documented as the mechanism of location-cued visual attention in different situations. External noise exclusion is, naturally, exhibited in conditions with high external noise in the stimulus. Pure external noise exclusion occurs when attention improves performance only in high noise, yet has little or no effect in conditions of low or no external noise [11, 17]. This corresponds to an external noise exclusion signature (Fig. 2e). External noise exclusion was the primary mechanism of attention in comparisons of early versus late location cuing and in contrasts between valid and invalid pre-cues to location. Stimulus enhancement is demonstrated by improvements due to attention in the absence of external noise, but cannot improve performance when it is limited by external noise. This is because stimulus enhancement must affect external noise and (external) signal in the stimulus in exactly the same way. Pure stimulus enhancement occurs when attention improves performance in low external noise, but is ineffective in high external noise conditions [1, 2, 5, 10]. This is the stimulus enhancement signature (Fig. 2b).

External noise exclusion was shown to be an important mechanism of spatial attention in complex multiple-location displays [11, 15, 21] with either central [11, 17, 22] or peripheral [22] location cues. Attention was found to have little effect on performance in high noise, and hence little impact of external noise exclusion, in displays with as few as two locations, but increasingly large effects on performance for displays with 4 or more locations. These results held for cue validity effects and for cue advancement effects for both Gabor orientation discrimination and for letter identification performance. However, external noise exclusion was substantial, and of approximately the same size, for both central and peripheral pre-cueing. Thus, external noise exclusion is the primary mechanism of attention mediated by pre-cueing in a range of situations and tasks. In contrast, stimulus enhancement was shown to occur largely in cases of peripheral cuing of location [1, 2, 5, 22].

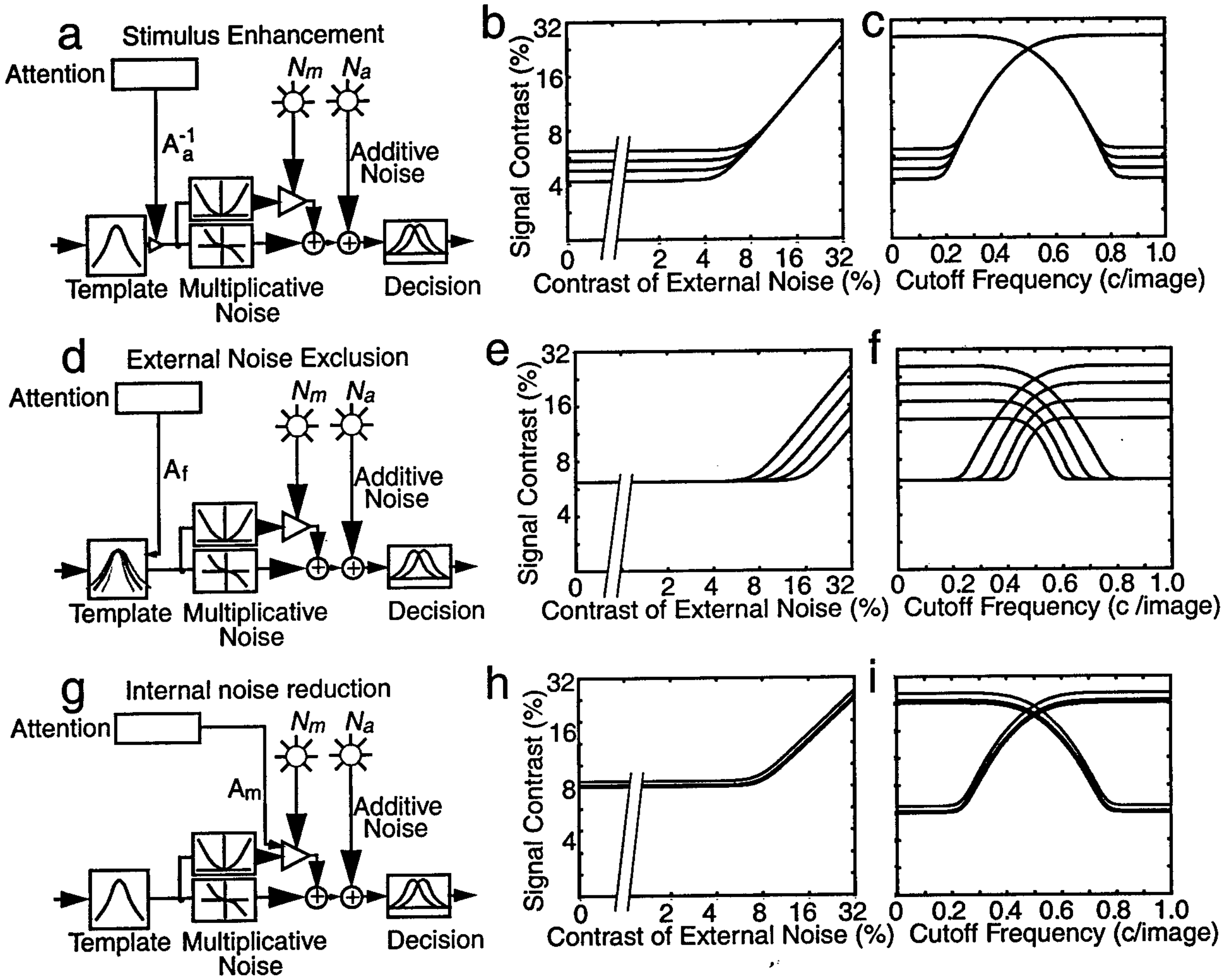

Figure 2. Three mechanisms of visual attention and their performance signatures. (b,e,h) show attention effects on threshold contrasts with increasing external noise levels; (c,f,i) show attention effects on threshold contrasts for filtered external noise as a function of cutoff frequency.

This model structure has already proved useful in recasting and reorganizing existing literature in the area [21, 22]. Results previously considered to be inconsistent can be systematized in terms of the presence of external noise or masks, the nature of an attention pre-cue (either peripheral or central), and the location load of the display. Improvements in accuracy associated with pre-cuing of location in the literature are predominantly clustered in masked, multi-location displays.

These empirical findings show that (a) the mechanisms identified using the external noise paradigm in the domain of attention can be observed separately and in different circumstances, (b) external noise exclusion occurs in both peripheral and central pre-cuing of attention, (c) external noise exclusion is increasingly important in multi-location displays of larger size and complexity, and (d) stimulus enhancement is primarily associated with peripheral pre-cues.

During the project period, an observer model, the Perceptual Template Model [1, 2, 5], was created and developed to quantitatively analyze data based in the external noise paradigm (a). Subsequently, a number of theoretical developments were also completed: (b) the relation of the PTM model to earlier observer models along with specific tests for the elaborated model were detailed in [2, 3]; (c) specific tests for mixtures of mechanisms were developed in [3, 4, 8, 21], and (d) internal ratio tests of the model in [3]. (e) Analysis of a full stochastic form of the model appears in [21]. These formal developments of quantitative tests for the form of the observer model, and more specifically for the discrimination of mechanism mixtures are powerful tools that can be applied directly in further analysis of spatial attention.

The PTM model framework can be used to estimate the spatial frequency sensitivity of the template [24, 25, 27]. External noise filtered in various pass-bands is used to determine which spatial frequencies of noise affect the performance of the observer. Eliminating external noise from spatial frequency bands to which the observer's template is not sensitive leaves performance unaffected. The PTM model was extended to the pass-band noise tests to estimate the shape of the perceptual template [24]. This method was used to evaluate changes in the tuning of the perceptual template as a function of attention [25, 27]. In the case of narrow spectrum Gabor targets, attention did not alter the spatial frequency sensitivity of observers but had their effect through improved temporal and spatial focusing [27]. In the case of broad spectrum oriented character targets, attention improved the match of the perceptual template to the spatial frequency composition of the characters as well as improving temporal and spatial focusing [25].

The external noise method was also applied to the domain of perceptual learning [4, 8, 13]. Perceptual learning was studied in the presence of a parametrically varied external noise for peripheral tasks in the presence of a foveal task designed to guarantee eye fixation. Perceptual learning involved both learning of external noise exclusion and of stimulus enhancement. These data also illustrated very strong ratio properties between data collected at a higher threshold level and lower threshold level. These strong quantitative properties allow one consider and rule out possible changes in system non-linearity.

Additionally, two visual search projects were completed that evaluated the architecture and processing limits of visual search in the absence of eye movements [7, 12, 26].

4.4 Details of Projects

The primary journal articles resulting from this project are described in more detail in the abstracts in the next sections.

Lu, Z.-L. & Dosher, B. A., External noise distinguishes mechanisms of attention. *Vision Research*, **38**, 1183-1198, 1998.

We developed and tested a powerful method for identifying and characterizing the effect of attention on performance in visual tasks as due to *signal enhancement, distractor exclusion,* or *internal noise suppression.* Based on a noisy Perceptual Template Model (PTM) of a human observer, the method adds increasing amounts of external noise (white Gaussian random noise) to the visual stimulus and observes the effect on performance of a perceptual task for attended and unattended stimuli. The three mechanisms of attention yield three "signature" patterns of performance. The general framework for characterizing the mechanisms of attention is used here to investigate the attentional mechanisms in a concurrent location-cued orientation discrimination task. Test stimuli - Gabor patches tilted slightly to the right or left - always appeared on both the left and the right of fixation, and varied independently. Observers were cued on each trial to attend to the left, the right, or evenly to both stimuli, and decide the direction of tilt of both test stimuli. For eight levels of added external noise and three attention conditions (attended, unattended, and equal), subject's contrast threshold levels were determined. At low levels of external noise, attention affected threshold contrast: threshold contrasts for nonattended stimuli were systematically higher than for equal attention stimuli, which were in turn higher than for attended stimuli. Specifically, when the rms contrast of the external noise is below 10%, there is a consistent 17% elevation of contrast threshold from attended to unattended condition across all three subjects. For higher levels of external noise, attention conditions did not affect threshold contrast values at all. These strong results are characteristic of a signal enhancement, or equivalently, an internal additive noise reduction mechanism of attention.

Dosher, B. & Lu, Z.-L. Perceptual learning reflects external noise filtering and internal noise reduction through channel selection. *Proceedings of National Academy, USA*, **95**, 13988-13993, 1998.

The first systematic measurement of perceptual learning by human adults in both noiseless and noisy environments is reported. These measurements provide key insights into the mechanisms of perceptual learning. The task was orientation discrimination in visual periphery. The signal contrasts required to achieve threshold were reduced following training by a factor of two or more at all levels of environmental noise, reflecting a combination of stimulus enhancement and exclusion of external noise. Observers learned to respond only to those low level visual channels that are most closely tuned to the signal in the task. Thus, perceptual learning may reflect plasticity in the weighting of the activity of low-level visual channels for a particular task.

Details of Projects (continued)

Lu, Z.-L. & Dosher, B. Characterizing human perceptual inefficiencies with equivalent internal noise. *Journal of Optical Society of America, A*, **16**, 764-778, 1999.

A widely used method for characterizing and comparing inefficiencies in perceptual processes is the method of *equivalent internal noise* -- the amount of random internal noise necessary to produce the degree of inefficiency exhibited by the perceptual system in processing [J. Opt. Soc. Am., 46, 634 (1956)]. The amount of *equivalent* internal noise is normally estimated by systematically increasing the amount of external noise added to the signal stimulus and observing how threshold -- signal stimulus energy required for an observer to maintain a given performance level -- depends on the amount of external noise. In a variety of perceptual tasks, a simple noisy linear amplifier model [D. Pelli, Ph. D. dissertation, University of Cambridge, Cambridge, UK,1981) has been utilized to estimate the equivalent internal noise $N_{internal}$ by fitting the relation between threshold contrast c_τ and external noise N_{ext} at a single (d') performance level: $c_\tau^2 = (d'/\beta)^2 [N_{ext}^2 + N_{internal}^2]$. This model makes a strong prediction: Independent of observer and external noise contrast, the ratio between two thresholds at each external noise level is equal to the ratio of the two corresponding d''s. This potential test for the internal consistency of the model had never been examined previously. Here, we estimated threshold ratios between multiple performance levels at various external noise contrasts in two different experiments: Gabor orientation identification and Gabor detection. We found that, in both identification and detection, the observed threshold ratios between different performance levels departed substantially from the d' ratio predicted by the simple noisy linear amplifier model. An elaborated Perceptual Template Model (PTM) [Vis. Res., 38, 1183 (1998)] with nonlinear transducer functions and multiplicative noise in addition to the additive noise in the simple linear amplifier model leads to a substantially better description of the data, and suggests a reinterpretation of earlier results relying on the simple noisy linear amplifier model. The relationship of our model and method to other recent parallel and independent developments [J. Opt. Soc. Am. A, 14, 2406 (1997)] is discussed.

Details of Projects (continued)

Dosher, B. & Lu, Z.-L. Mechanisms of perceptual learning. *Vision Research*, **39**, 3197-3221, 1999.

Systematic measurements of perceptual learning were performed in the presence of external or stimulus noise. In the new external noise method (Dosher & Lu, 1997; Lu & Dosher, 1998) increasing amounts of external noise (white Gaussian random noise) is added to the visual stimulus in order to identify mechanisms of perceptual learning. Performance improved (threshold contrast was reduced) over days of practice on a peripheral orientation discrimination task - labelling Gabor patches as tilted slightly to the right or left. Practice improvements were largely specific to the trained quadrant of the display. Performance improved at all levels of external noise. The external noise method and Perceptual Template Model (PTM) of the observer identifies the mechanism(s) of performance improvements as due to *stimulus enhancement, external noise exclusion,* or *internal noise suppression.* The external noise method was further extended by measuring thresholds at two threshold performance levels, allowing identification of mixtures in the PTM model. Perceptual learning over 8-10 days improved the "filtering" or exclusion of external noise by a factor of two or more, and improved suppression of additive internal noise - equivalent to stimulus enhancement - by fifty percent or more. Coupled improvements in external noise exclusion and stimulus enhancement in the PTM model may reflect channel weighting. Perceptual learning may not reflect neural plasticity at the level of basic visual channels, nor cognitive adjustments of strategy, but rather plasticity at an intermediate level of weighting inputs to decision.

Lu, Z.-L., Liu, C. Q. & Dosher, B. A. Attention mechanisms for multi-location first- and second-order motion perception, *Vision Research*, **40**, 173-186, 2000.

We applied the external noise plus attention paradigm to study attention mechanisms involved in *concurrent* first-order and second-order motion perception at two spatial locations. Cued to attend to one of the locations, the observer was instructed to independently judge direction of motion of either first-order (Experiment 1) or second-order (Experiment 2) motion stimuli at both locations in every trial. Across trials, systematically controlled amounts of external noise was added to the motion displays. We measured motion threshold at three performance criteria in every attention X external noise condition. We find that observers could, without any loss, simultaneously compute first-order motion direction at two widely separated spatial locations across a broad range of external noise conditions. However, considerable loss occurred at the un-attended location in processing second-order motion direction at two separated spatial locations. We conclude that, under the conditions investigated in the current study, (1) in first-order motion perception, the visual system could simultaneously process motion direction at two widely separated locations without any capacity limitation; (2) in second-order motion perception, attending to a spatial location enhances stimulus contrast at that location by a factor of about 1.37 (or equivalently, reduces the internal additive noise by a factor of about 0.73.).

Details of Projects (continued)

Dosher, B.& Lu, Z.-L. Mechanisms of perceptual attention in precuing of location. *Vision Research*, **40**, 1269-1292, 2000.

What are the mechanisms of spatial attention underlying precue validity effects? We answer this question within the framework of a perceptual template model (PTM) [Lu & Dosher (1998). External noise distinguishes attention mechanisms. *Vision Research*, 38, 1183–1198; Dosher & Lu (1999). Mechanisms of perceptual learning. *Vision Research*, 39, 3197–3221] and an external noise plus attention paradigm for orientation judgments in two- to eight-location displays. Attentional mechanisms correspond to behavioral signatures: External noise exclusion produces cuing effects in high external noise and stimulus enhancement produces cuing effects in noiseless displays. We found that external noise exclusion was the primary mechanism of cue validity effects, with large effects in high-noise displays. Stimulus enhancement coexisted as a secondary mechanism in noiseless displays for a subset of observers and display conditions. Contrast threshold ratio tests ruled out attentionally mediated changes in gain control. The ratio rules were also shown to hold for a stochastic PTM model. Effects were equivalent for four-alternative (Experiment 1) and two-alternative (Experiment 2) orientation identification. Precues allow observers to reduce noise and focus on the target in the precued location. External noise exclusion was more important in larger displays. Previous results are reclassified and understood within the PTM framework.

Lu, Z.-L. & Dosher, B.Spatial attention: Different mechanisms for central and peripheral cues?, *Journal of Experimental Psychology: Human Perception and Performance*, **26**, 1534–1548, 2000.

The external noise paradigm (Lu & Dosher, 1998) was applied to investigate mechanisms of spatial attention in location precuing. Observers were precued or simultaneously cued to identify 1 of 4 pseudocharacters embedded in various amounts of external noise. The cues were either central or peripheral. Both central and peripheral precuing significantly reduced threshold in the presence of high external noise (16% and 17.5%). Only peripheral precuing significantly reduced threshold in the presence of low, or no, external noise (11%). A perceptual template model identified different mechanisms of attention for central and peripheral precuing, external noise exclusion for central precuing, and a combination of external noise exclusion and stimulus enhancement (or equivalently, internal additive noise reduction) for peripheral cuing.

Details of Projects (continued)

Lu, Z.-L. & Dosher, B., Characterizing the spatial-frequency selectivity of perceptual templates, *Journal of the Optical Society of America, A*, in press.

Filtered external noise has been an important tool in characterizing the spatial-frequency sensitivity of perceptual templates. Typically, low-pass and/or high-pass filtered external noise is added to the signal stimulus. Thresholds --- signal energy necessary to maintain given criterion performance levels --- are measured as functions of the spatial-frequency pass-band of the external noise (TVF's). An observer model is postulated to segregate the impact of the external and the internal noise. The spatial-frequency sensitivity of the perceptual template is determined by the relative impact exerted by *external noise* in each frequency band. The Perceptual Template Model (PTM) is a general observer model which provides an excellent account of human performance in white external noise [Vis. Res., **38**, 1183 (1998); J. Opt. Soc. Am., A., **16**, 764 (1999)]. Here, we further develop the PTM for filtered external noise and apply it to derive the spatial-frequency sensitivity of perceptual templates.

Lu, Z.-L. & Dosher, B., Attention fine-tunes perceptual templates in spatial cuing, submitted.

In responding to a target that could appear at one of several locations, informing observers about its location before stimulus onset usually leads to improved performance in accuracy and response time. The mechanisms underlying this and other spatial attention effects have fascinated scientists from sensory physiologists studying cellular functions to psychologists researching the basis of human behavior. At the single cell level, animal studies suggest that neurons in some cortical regions could exclude unwanted information by shrinking their receptive fields to only include the target. Whereas human brain imaging results are largely consistent with this view, attentional enhancement of neuronal response and selectivity have also been reported. At the observer level, we have devised psychophysical paradigms to distinguish three mechanisms of attention, and identified external noise exclusion and stimulus enhancement as the primary and secondary mechanisms of spatial attention. Here, we evaluated two different methods of external noise exclusion, i.e., tuning of perceptual templates in spatial extent (related to shrinking of neural receptive field) and spatial frequency selectivity (related to sharpening of neural tuning characteristics). We found that both are used by spatial attention to exclude external noise at the attended location.

Dosher, B., Han, S.-M. & Lu, Z.-L., Time course of asymmetric visual search. Submitted.

The difficulty of finding a target item among distractors depends on the choice of target and distractor, even for the same items. For example, searching for a C among Os is easier than searching for an O among Cs. Such search asymmetries are thought to reveal the coding of basic visual features. The time to search displays with the more difficult target –distractor combination depends more strongly on display size, a result that is often attributed to attention-demanding serial search processes. This paper uses a speed-accuracy method to measure the time course of processing in asymmetric visual search in time-limited displays without eye-movements. The asymptotic accuracy for visual search was lower for the more difficult target-distractor assignment (O among Cs) and for larger display sizes. The dynamics of visual search were, however, essentially independent of display size. A probabilistic parallel search model accounted well for both the speed and accuracy of visual search in the absence of eye movements.

5. PERSONNEL SUPPORTED

Principle Investigator. Barbara Anne Dosher, Professor of Cognitive Science. As projected in the original proposal, the PI devoted 15% time during 9 month academic year at no cost plus 35 days, 25 days and 25days, respectively, in the summers of 1998, 1999, and 2000..

Graduate Research Assistant. Ms. Songmei Han. Ms.Han has just advanced to candidacy for the Ph.D. degree in the Department of Cognitive Science, University of California, Irvine, CA. She has been working on the attention mechanisms involved in limitations in processing multiple features or tasks in relation to object attention. She has also worked on projects on processing limitations in visual search. Ms. Han worked on the project over a several year period under support by the University of California, Irvine, and by the Institute of Mathematical Behavioral Science. She was supported by this project for 100% in7 weeks in the Summer of 2000.

Undergraduate Research Assistants. A number of undergraduate students worked on this project over the grant period, on variable hour basis. These include: Ann Contarino (1998), Dan Herrera (199) Kaman (Kitty) Lee (1998-1999), Sapna Mehta (1998 Summer), Jimmy Ngo (1999), Vincy Choy (2000), Loubna Shokair (2000), Chei Yi (Jenny) Chen (2000), Kati Beiersdorf (Fall 2000), Kristen van Camerik (Fall 2000) These undergraduate assistants have been responsible for subject scheduling, data collection in a number of experiments, and library research.

6. PUBLICATIONS

1. Dosher, B. A. & Lu, Z-L., Attention to location mediated by internal noise reduction. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **38,** No.4, 687, 1997 (Abstract)
2. Lu, Z.-L. & Dosher, B. A., Characterizing attention mechanisms. *Bulletin of the Psychonomics Society*, **38**: 58, 1997. (Abstract).
3. Lu, Z.-L. & Dosher, B. A., Characterizing human perceptual inefficiencies. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **39,** No. 4, 625, 1998 (Abstract)
4. Dosher, B. A. & Lu, Z.-L., Mechanisms of perceptual learning. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **39,** No. 4, 912, 1998. (Abstract)
5. Lu, Z.-L. & Dosher, B. A., External noise distinguishes mechanisms of attention. *Vision Research,* **38**, 1183-1198, 1998.
6. Lu, Z.-L. & Dosher, B. A., Distractor exclusion underlies improvement in form discrimination following a location precue. *Bulletin of the Psychonomics Society*, **39**, 1998. (Abstract).
7. Dosher, B. A., Han, S.-M. & Lu, Z.-L., Time course of visual search among homogeneous and heterogeneous distractors. *Bulletin of the Psychonomics Society*, **39**, 1998, (Abstract).
8. Dosher, B. & Lu, Z.-L. Perceptual learning reflects external noise filtering and internal noise reduction through channel selection. *Proceedings of National Academy, USA,* **95,** 13988-13993, 1998.
9. Lu, Z.-L. & Dosher, B. Characterizing human perceptual inefficiencies with equivalent internal noise. *Journal of Optical Society of America, A,* **16**, 764-778, 1999.
10. Liu, C. Q., Lu, Z.-L. & Dosher, B. A., Attention in first- and second-order motion perception. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **40**, No. 4, S973, 1999. (Abstract)
11. Dosher, B. A. & Lu, Z.-L., Attention to a validly cued location improves performance by excluding external noise. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **40**, No. 4, S797, 1999. (Abstract)
12. Han, S.-M., Dosher, B. A. & Lu, Z.-L., A parallel model accounts for the time course of a difficult visual search task. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **40**, No. 4, S344, 1999. (Abstract)
13. Dosher, B. & Lu, Z.-L. Mechanisms of perceptual learning. *Vision Research,* **39**, 3197-3221, 1999.
14. Lu, Z.-L. & Dosher, B. A., Attention fine-tunes perceptual templates in spatial cuing. *Bulletin of the Psychonomics Society*, **40**, 52, 1999 (Abstract)
15. Dosher, B. A. & Lu, Z.-L., Mechanisms of perceptual attention in multilocation cuing. *Bulletin of the Psychonomics Society*, **40**, 34, 1999 (Abstract)
16. Lu, Z.-L., Liu, C. Q. & Dosher, B. A. Attention mechanisms for multi-location first- and second-order motion perception, *Vision Research,* **40**, 173-186, 2000.

17. Dosher, B. & Lu, Z.-L. Noise exclusion in spatial attention. *Psychological Science*, **11**, 139-146, 2000.
18. Lu, Z.-L. & Dosher, B. A., Different mechanisms of attention for central and peripheral precuing. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **41**, No. 4, S42, 2000. (Abstract)
19. Dosher, B. A. & Lu, Z.-L., Perceptual templates in spatial attention. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **41**, No. 4, S750, 2000. (Abstract)
20. Han, S.-M., Dosher, B. A. & Lu, Z.-L., A time course analysis of asymmetric visual search. *Investigative Ophthalmology and Visual Science, ARVO Supplement*, **41**, No. 4, S423, 2000 (Abstract)
21. Dosher, B.& Lu, Z.-L. Mechanisms of perceptual attention in precuing of location. *Vision Research*, **40**, 1269-1292, 2000.
22. Lu, Z.-L. & Dosher, B.Spatial attention: Different mechanisms for central and peripheral cues?, *Journal of Experimental Psychology: Human Perception and Performance*, **26**, 1534–1548, 2000.
23. Dosher, B., Han, S.-M., & Lu, Z.-L., Time course of asymmetric visual search. *Perception, Supplement*, **29**, 12d, 2000. (Abstract)
24. Lu, Z.-L. & Dosher, B., Characterizing the spatial-frequency selectivity of perceptual templates, *Journal of the Optical Society of America, A*, in press.
25. Lu, Z.-L. & Dosher, B., Attention fine-tunes perceptual templates in spatial cuing, submitted.
26. Dosher, B., Han, S.-M. & Lu, Z.-L., Time course of asymmetric visual search. Submitted.
27. Dosher, B., & Lu, Z.-L. (in preparation) Changes in the perceptual filter following valid spatial pre-cues of attention.

7. INTERACTIONS/TRANSITIONS

Conference Presentations

1. Dosher, B. A. & Lu, Z-L., Attention to location mediated by internal noise reduction. Talk given by Dosher at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'97), Fort Lauderdale, Florida, 1997.
2. Lu, Z.-L. & Dosher, B. A., Characterizing attention mechanisms.T alk given by Lu at the 38th Annual Meeting of the Psychonomics Society, Philadelphia, PA, 1997.
3. Dosher, B. A. & Lu, Z.-L., Mechanisms of perceptual learning. Talk given by Dosher at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'98), Fort Lauderdale, Florida, 1998
4. Lu, Z.-L. & Dosher, B. A., Characterizing human perceptual inefficiencies. Poster given by Lu at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'98), Fort Lauderdale, Florida, 1998.

5. Lu, Z.-L. & Dosher, B. A., Distractor exclusion underlies improvement in form discrimination following a location precue. Talk given by Lu at the 39th Annual Meeting of the Psychonomics Society, Dallas, Texas, 1998.
6. Dosher, B. A., Han, S.-M. & Lu, Z.-L., Time course of visual search among homogeneous and heterogeneous distractors. Talk given by Dosher at the 39th Annual Meeting of the Psychonomics Society, Dallas, Texas, 1998.
7. Lu, Z.-L. & Dosher, B. A., Using external noise to define mechanisms of attention. Talk given by Lu at the 24nd Annual Interdisciplinary Conference, Jackson Hole, Wyoming, 1999.
8. Dosher, B. A. & Lu, Z.-L., Mechanisms of perceptual learning. Talk given by Dosher at the 24nd Annual Interdisciplinary Conference, Jackson Hole, Wyoming, 1999.
9. Dosher, B. A. & Lu, Z.-L., Mechanisms of perceptual attention,. Invited talk given by Dosher at the 3rd Annual Vision Research Conference: Preattentive and Attentive Mechanisms in Vision, Fort Lauderdale, Florida, 1999.
10. Lesmes, L. A., Lu, Z.-L. & Sperling, G., The mechanism of isoluminant motion perception is third-order motion. Talk given by Lesmes at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'99), Fort Lauderdale, Florida, 1999.
11. Liu, C. Q., Lu, Z.-L. & Dosher, B. A., Attention in first- and second-order motion perception. Talk given by Liu at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'99), Fort Lauderdale, Florida, 1999.
12. Dosher, B. A. & Lu, Z.-L., Attention to a validly cued location improves performance by excluding external noise. Talk given by Dosher at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'99), Fort Lauderdale, Florida, 1999.
13. Han, S.-M., Dosher, B. A. & Lu, Z.-L., A parallel model accounts for the time course of a difficult visual search task. Poster given by Han at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'99), Fort Lauderdale, Florida, 1999.
14. Lu, Z.-L. & Dosher, B. A., Attention fine-tunes perceptual templates in spatial cuing. Talk given by Lu at the 40h Annual Meeting of the Psychonomics Society, Los Angeles, California, 1999.
15. Dosher, B. A. & Lu, Z.-L., Mechanisms of perceptual attention in multilocation cuing. Talk given by Dosher at the 40h Annual Meeting of the Psychonomics Society, Los Angeles, California, 1999.
16. Lu, Z.-L. & Dosher, B. A., Different mechanisms of attention for central and peripheral precuing. Poster given by Lu at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'00), Fort Lauderdale, Florida, 2000.
17. Dosher, B. A. & Lu, Z.-L., Perceptual templates in spatial attention. Talk given by Dosher at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'00), Fort Lauderdale, Florid, 2000.
18. Han, S.-M., Dosher, B. A. & Lu, Z.-L., A time course analysis of asymmetric visual search. Poster given by Han at the annual meeting of the Association for Research in Vision and Ophthalmology (ARVO'00), Fort Lauderdale, Florida, 2000.

19. Dosher, B., Han, S.-M., & Lu, Z.-L., Time course of asymmetric visual search. Poster presentation at the 9th European Congress on Visual Perception, Groningen, the Netherlands, 2000.

Invited Talks

1. Dosher, B. A. & Lu, Z.-L., Mechanisms of perceptual attention,. Invited talk given by Dosher at the 3rd Annual Vision Research Conference: Preattentive and Attentive Mechanisms in Vision, Fort Lauderdale, Florida, 1999.
2. Dosher, B. (1999). Mechanisms of attention. Department of Psychology University of California, Berkeley, Invited Colloquium, December.
3. Dosher, B. (2000). Mechanisms of performance enhancement in attentional and learning tasks. California Institute of Technology. Invited Colloquium, March.
4. Dosher, B.Mechanism of spatial attention, invited talk given by Dosher in the AFOSR Attention Forum, Dayton, Ohio, 2000.
5. Dosher, B. (2000) Mechanisms of spatial attention and perceptual learning. Center for Cognitive Science, Rutgers University. Invited Colloquium, April
6. Dosher, B. (2000). Representation and relational processing in working memory. Association for Research in Vision and Opthalmology, May. Invited Conference Symposium Talk.

8. NEW DISCOVERIES, INVENTIONS, or PATENT DISCLOSURES

None.

9. HONORS/AWARDS

Dosher, B. Elected Fellow of the Society for Experimental Psychologists, 1997.